Radial Acceletron, A New Low-Impedance HPM Source

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***Abstract*—The transit-time effect in a coaxial structure was explored to develop a low-impedance high-power microwave (HPM) source that uses no external magnetic field and no confining foils. This source will work in the 1–20 GHz range and will have a power output of no less than 1 GW. The input will be a low-voltage dc pulse of only 350 kV or less with a flat top of approximately 200 ns. The dc pulse is launched into a coaxial structure that is the diode, the oscillator, and the buncher all in one. The source offers significant improvements in power, repetition rate, size, and efficiency. Because of the coaxial structure, the diode impedance may be reduced to a few ohms thus allowing larger input and output powers. With no foils to erode, the only factor limiting the repetition rate is the ability to maintain an adequate vacuum, and since there is no external magnetic field required, the device is simple, lightweight, and inexpensive. Because of the strong bunching, the efficiency is high. As is the case with all transit-time oscillators, the signal is stable and monochromatic. The device may be used as a buncher or as an oscillator. It is shown that a device based on this concept is indeed possible. In addition, it is shown that the gated emission of electrons, a process basic to high-power RF amplification, is a natural by-product of the mechanism used in this device.**

I. Introduction

ACCELERATED motion of electric charges is the source of all electromagnetic radiation. Fields of characteristic modes of high Q conducting structures can be used as an accelerating mechanism for coherent radiation from charged particle beams in the microwave range [1]–[6]. For instance, when streaming charged particles cross a cavity resonating at one of its characteristic modes, the decelerating fields of the mode, under certain conditions, can cause the charges to radiate coherently, thereby losing some of their kinetic energy and enhancing the fields. This process, known as "transit-time" effect, has been understood since the 1930's. However, mainly because of very low growth rate and partly because of low saturation levels, no significant amount of microwave radiation has been produced with the nonrelativistic charged particle beams available until now. An attempt in increasing the beam current in order to increase the power would result in strong space charge depression and formation of virtual cathode. Recent advancements in pulse-power technology has made relativistic kiloamp beams possible, thereby reviving the transit-time oscillators (TTO's) as a possible source of high-power microwave (HPM) radiation. Since the resonating structure has a strong stabilizing effect on the process, HPM sources based on TTO's are robust, stable, monochromatic, and efficient

The radial acceletron is one such new source. In addition, because of its cylindrical structure, it is a very low-impedance (high-power) device. Also, because it combines the oscillator with the diode, it needs no anode foils, so it can be repetitively pulsed at a very high rate. Furthermore, for the modes explored here, the radial acceletron uses no external magnetic field so it is very compact and lightweight. In Section II the theory involved in radial acceletron is explored. The results of numerical simulations are presented in Section III. Section IV is the conclusion and suggestions for follow-up work.

II. Theory

We start with a brief qualitative description of the theory of transit-time oscillators. When charged particles cross a structure with standing RF waves they undergo a series of accelerations and decelerations. If the particles' transit-time is close to the period of the RF and the radiation is the lowest mode in the direction of the transit, there will be one acceleration and one deceleration in an order that depends on the phase at the time of entry. Those particles who accelerate first and decelerate next will travel faster than the average and have gained some kinetic energy upon leaving. Those particles that enter at a decelerating phase, however, will spend more time in the cavity than the average transit time. These particles lose more kinetic energy than those of the opposite phase gained. The overall result is a net flow of energy from the beam to the fields. This process continues until the average transit time becomes significantly different from the initial transit time and the fields cease to grow any further.

In an acceletron this process takes place in a diode and the particles are, in addition to the RF fields, also subject to the dc fields of the diode. This allows for an extermely compact system because the diode and the resonating cavity are combined into one. In addition, the uniform acceleration due to the dc fields raises the space-charge-limited current, thus allowing more current at a lower voltage. Combining the diode and the resonator also eliminates the need for foils in the path of the beam, thus allowing for very high repetition rate.

In a *radial* acceletron, the diode/resonator has a coaxial structure that allows for much smaller diode impedances and consequently higher power for any given voltage. Fig. 1 is a schematic drawing of a radial acceletron with coaxial loading. It consists of two coaxial lines sharing the same outer conductor. The inner conductor to the left is the cathode, enlarged at the emission area to enhance the fields and to

Manuscript received October 22, 1995; revised March 7, 1996.
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Publisher Item Identifier S 0093-3813(96)05184-3.

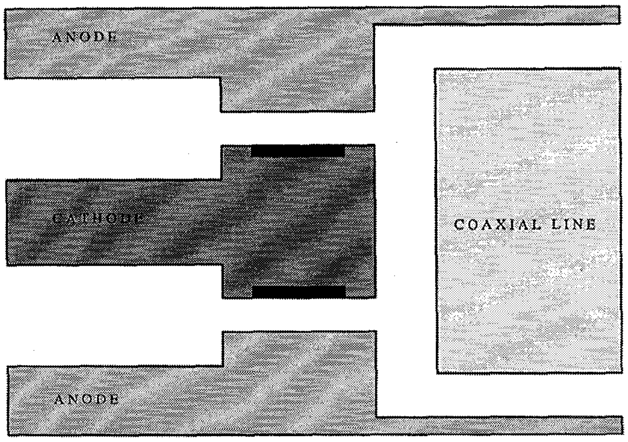

Fig. 1. Schematic plot of the radial acceletron with radial loading. The dc pulse is launched from the left.

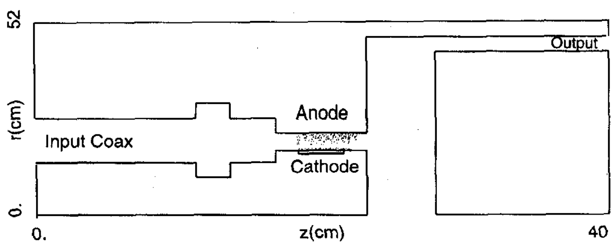

Fig. 2. Computer simulation of the radial acceletron showing the electron in a gated emission pattern. The Bragg reflectors in the input line are for confining the RF fields. Only the upper portion of the device is modeled.

increase the emission surface. The dc pulse is launched from the left. The electrons move radially toward the anode and radiate in the process. The radiation is extracted through the coaxial line to the right.

A. Small-Signal Analysis

The most complete solution to the radial acceletron problem is to solve the Maxwell's equations for the entire system and find the fields and the current self-consistently as a function of time. This approach is, however, intractable because of the complicated boundary conditions involved. In the small-signal gain approximation, the fields are initially assumed known eigenmodes of the system and the current is assumed fixed. The nonlinear effects, if any, and the space charge effect are ignored in this approximation and the saturation mechanism cannot be addressed. In this approximation, the energy exchange between the beam and the RF radiation may be described by

$$\frac{d\,(\text{Energy})}{dt} = \int_{\text{beam}} (\vec{J} \cdot \vec{E})\, dV \tag{1}$$

where $\vec{J}$ is the beam current, $\vec{E}$ is the sum of the dc field and the electric field of the eigenmode assumed present in the cavity, and the integration is over the beam volume. Furthermore, to assure analytic solution, nonrelativistic approximation is used and the calculation is carried out for a single particle. Generalization to a stream is trivial.

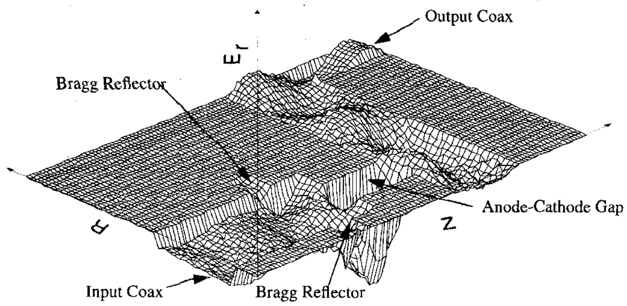

Fig. 3. Perspective plot of the radial electric field showing the RF being generated in the cavity, propagating radially outward toward the coaxial line and leaving the system through the coax.

Assuming a TM_{001} mode and a rectangular approximation to the eigenmode in the coaxial cavity, we integrate the equation of motion to get

$$v = \frac{eV}{md}t + \frac{eE_0}{m\omega}(\sin(\omega t + \phi) - \sin\phi) \tag{2}$$

where v is the velocity of the electron as a function of time, e is the electron charge, V is the dc voltage, m is the electron mass, d is the diode gap, E_0 is the amplitude of the assumed RF field, ω is the angular frequency of the RF, and ϕ is the phase at which the particle was emitted. Integrating (2) with respect to t over the gap gives

$$d = \frac{eV}{2md}\tau^2 - \frac{eE_0 \sin\phi}{m\omega}\tau - \frac{eE_0}{m\omega^2}(\cos(\omega\tau + \phi) - \cos\phi) \tag{3}$$

where τ is the transit time of the electron. If we further assume that the transit time τ is comparable to the period T of the RF, (3) reduces to

$$d = \frac{eV}{2md}\tau^2 - \frac{eE_0 \sin\phi}{m\omega}\tau. \tag{4}$$

Solving for τ and assuming $E_0 \ll (V/d)$ we have

$$\tau = \left(\frac{E_0 \sin\phi}{\omega V} - \sqrt{\frac{2m}{eV}}\right) d. \tag{5}$$

Substituting (5) in (2) gives the final velocity v_f as a function of $\phi, V,$ and d

$$v_f = \left(\frac{eE_0 \sin\phi}{m\omega} - \sqrt{\frac{2eV}{m}}\right) + \frac{eE_0}{m\omega} * \left[\sin\left(\frac{E_0 d \sin\phi}{V} - \omega d\sqrt{\frac{2m}{eV}} + \phi\right) - \sin\phi\right]. \tag{6}$$

v_d, the velocity gain due to the RF, is given by

$$v_d = v_{\text{dc}} - v_f = \sqrt{\frac{2eV}{m}} - v_f \tag{7}$$

where v_{dc} is the final velocity in the absence of RF. v_d averaged over ϕ changes sign with d, displaying alternating regions of growth and damping as a function of d. v_d is a measure of how much energy is being exchanged between the beam and the RF. This quantity may be summed over all electrons to find the growth rate for the RF radiation.

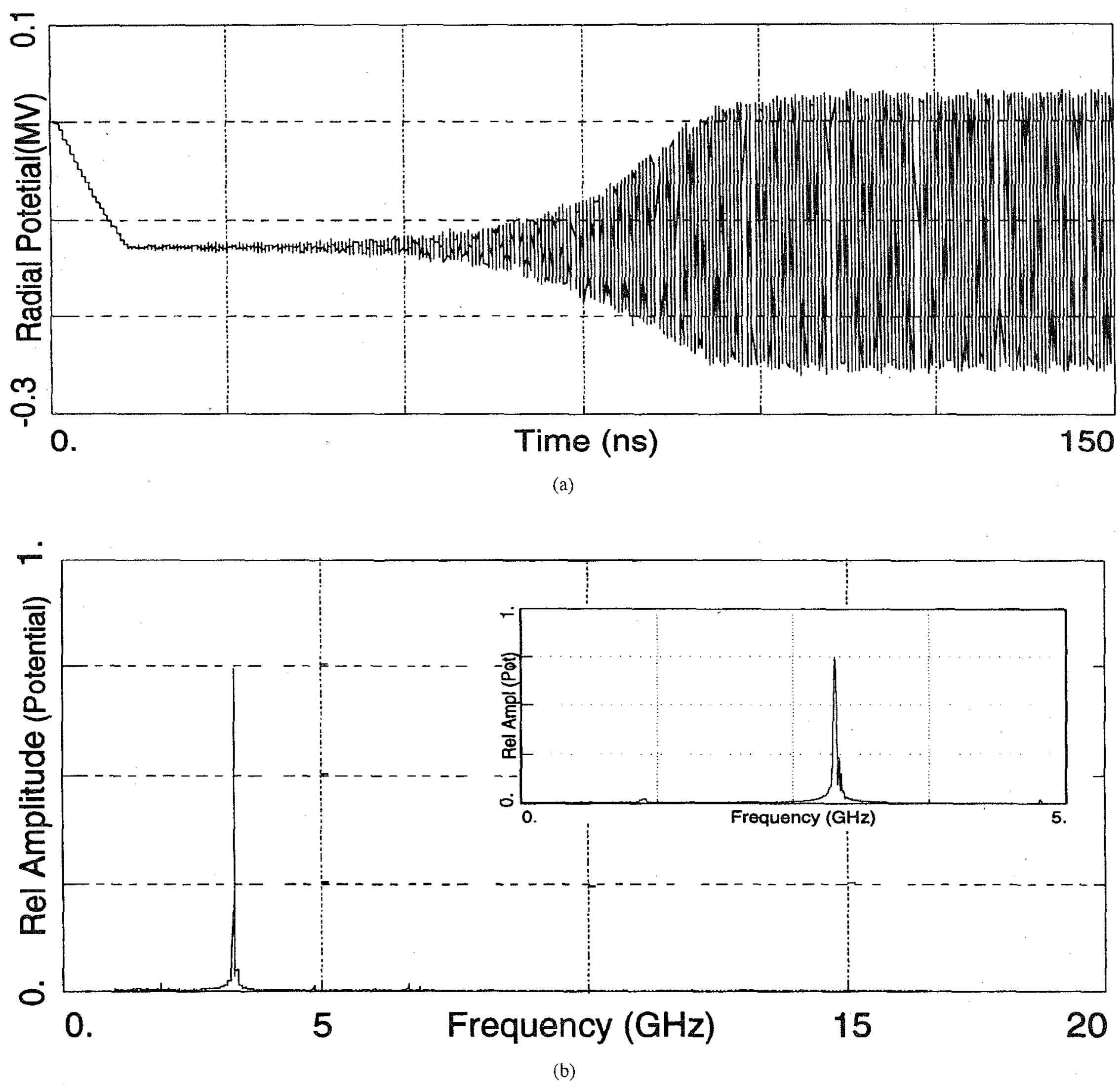

Fig. 4. (a) Time plot of the radial potential at the center of the resonator cavity. The amplitude of the ac voltage exceeds the dc value by a small fraction. (b) The Fourier transform of (a) showing a stable signal at approximately 3.1 GHz.

III. Simulation

The TM_{001} mode of the radial acceletron has been studied rather extensively using the two-dimensional (2-D) particle-in-cell (PIC) codes ISIS and MAGIC and the three-dimensional (3-D) PIC code SOS. The 2-D simulations were carried out to verify the principle behind the radial acceletron and to confirm its viability as a high power source of microwave. The 3-D simulations were performed to rule out the presence of nonaxisymmetric modes that could disturb the TM_{001} mode. A tentative axial loading of the device was also modeled using the 2-D code MAGIC. An unoptimized rms efficiency of 15% has been observed.

A. Two-Dimensional Simulations

The 2-D simulations were carried out for a device designed to produce the TM_{001} mode at 3.1 GHz operating at 250 kV. The choice of the TM_{001} mode was arbitrary; other modes and other frequencies are equally achievable. The radius of the inner conductor at the emission surface is 23.4 cm, the radius of the anode is 27.0 cm, making the A–K gap 3.6 cm wide, and the cavity is 6.4 cm long (see Fig. 1). The emission surface is only 3.2 cm long. The input line impedance is 20 Ω, the load impedance is 4 Ω, and the gap between the diode and the load is 8 cm wide. A short risetime of 5 ns for the dc pulse was applied to speed up the simulation. In some simulations, Bragg reflectors were used in the input line to increase the Q of the cavity.

Fig. 2 is a plot of particle trajectories as they move toward the anode. This corresponds to a time when the instability has saturated and the emission is fully modulated by the RF's electric field. The gap in the particle flow is caused by the RF electric field inhibiting emission during part of the period when it opposes and exceeds the dc field in the diode. During this time, the particles are either not emitted or reabsorbed by the cathode. In addition to this modulation, interaction with

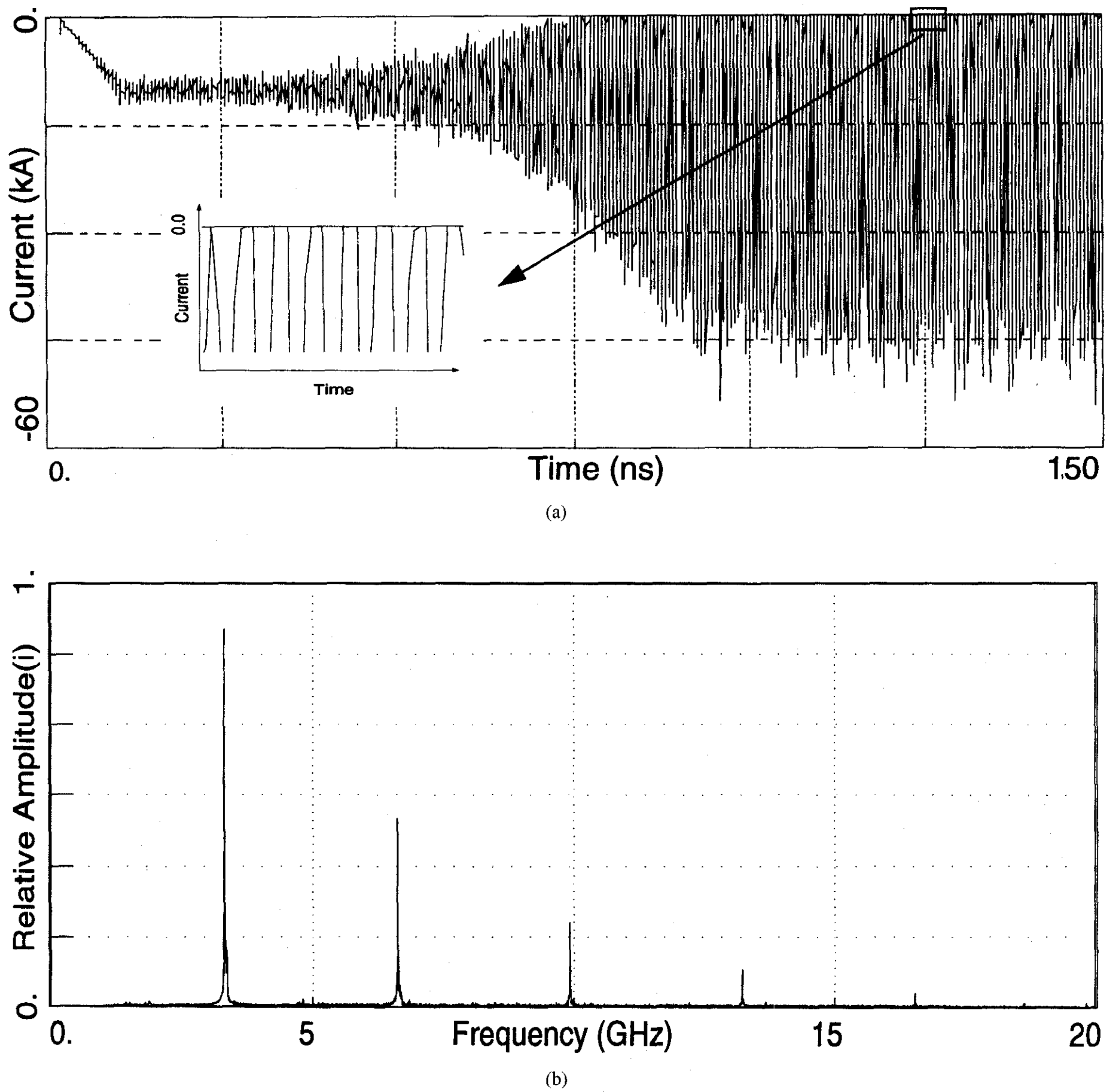

Fig. 5. (a) The time plot of the total radial current in the resonator cavity. The peak ac current is at least four times the dc level. (b) The Fourier transform of (a) showing up to five harmonics, an indication of a strongly bunched beam.

the RF has further bunched the beam to very high densities, an indication of possible high efficiency.

Fig. 3 is a perspective plot of the radial electric field showing the RF propagating along the gap and down the coaxial load to the right. The Bragg reflectors in the input line have reduced the backward-going RF to a very low level. Notice that the peak values of the RF amplitude in the coaxial load are larger than the dc amplitude in the input line. This picture, in absence of fields, will reduce to the grid mesh used in the simulation. The flat areas represent the conductor where the fields are zero.

Fig. 4(a) is the voltage at the center of the diode (i.e., E_r at the center integrated along the radius) plotted as a function of time. The amplitude of the RF is slightly larger than the magnitude of the input pulse. Fig. 4(b) is the Fourier transform of Fig. 4(a). It shows a pure TM_{001} mode with no indication of any mode competition.

Fig. 5(a) is the time plot of the total radial current crossing the diode gap (the cavity). The total dc current, $2\pi r j_r$, is approximately 11 kA. The peak RF current is approximately four times that, indicating very strong bunching. The Fourier analysis of the current time plot, Fig. 5(b), shows up to four harmonics present. The enlargement of the current plot near the zero line (inset) shows regions of zero current, caused by emission turn-off due to strong RF fields at the cathode. This modulated emission feature is similar to the gated emission patterns much desired in many RF related applications of intense electron beams.

Fig. 6(a) is a plot of the extracted RF power as a function of time. The peak power is approximately 500 MW, leading to an rms efficiency of 15%. No effort so far has been made in optimizing the loading and the extraction mechanism. Based on the bunching properties of the beam, the author is confident an overall rms efficiency of 25% is readily possible. Fig. 6(b)

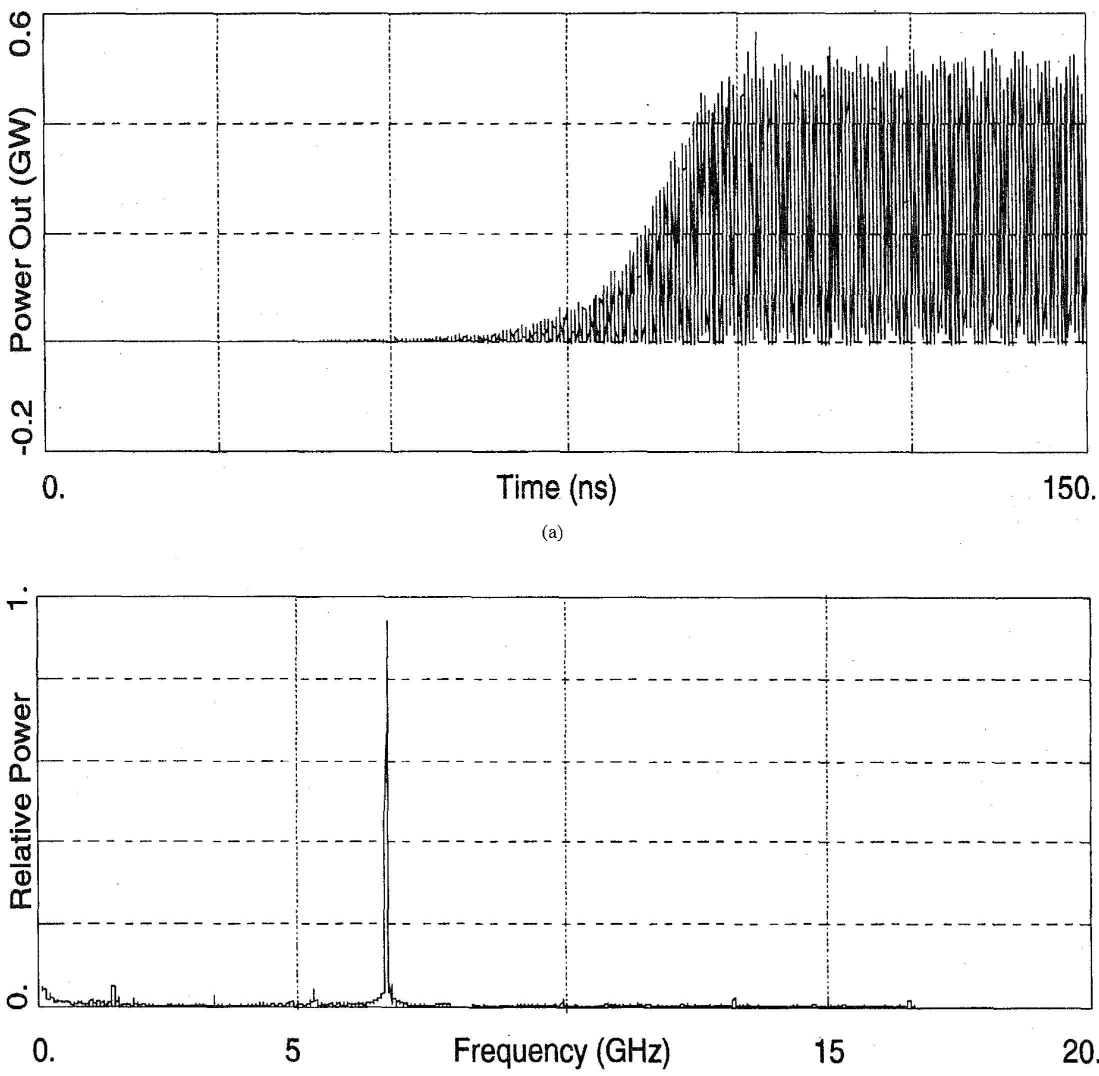

Fig. 6. (a) The time plot of the extracted power through a coaxial load showing a stable RF signal. The axial load is not optimized and the choice of axial extraction is not final. (b) The Fourier transform of (a) showing a monochromatic RF signal at twice the frequency of the RF fields.

is the Fourier transform of Fig. 6(a), showing the main peak at *twice* the frequency of the RF fields, as expected for the cross product of E and B used in the calculation of the power (Poynting flux). The presence of any dc fields would generate a cross term in the form of a constant times a sine function that would appear as a peak at the RF frequency in the power plot The lack of such peaks in this plot indicates that the extracted power is almost entirely ac radiation.

B. Three-Dimensional Simulations

The purpose of the 3-D simulations was to rule out the possibility of mode competition due to nonaxisymmetric modes. The acceletron with the TM_{001} mode is basically a 2-D problem. However, to model the nonaxisymmetric modes one needs to model the entire device. The device modeled in two dimensions was also modeled in three dimensions with the azimuthal angle ranging from 0 to 360°, in cylindrical geometry. The gridding was chosen to resolve any modes at TM_{333} or lower. No modes other than the TM_{001} mode were observed for the parameters used. Fig. 7 is a plot of the Fourier transform of the beam current from the 3-D simulation indicating there are no modes other than the mode observed in the 2-D simulation.

The 3-D PIC code SOS was used extensively for the 3-D simulations.

IV. Concluding Remarks and Future Work

The radial acceletron being a transit-time oscillator latches onto a characteristic mode of the structure supporting it and as such it produces a stable monochromatic radiation at a fixed frequency with little possibility of mode shifting or mode mixing. Furthermore, being an acceletron it allows the source to work at lower voltages ($\sim$250 kV) without forming a virtual cathode. Because of its radial mode of operation, the

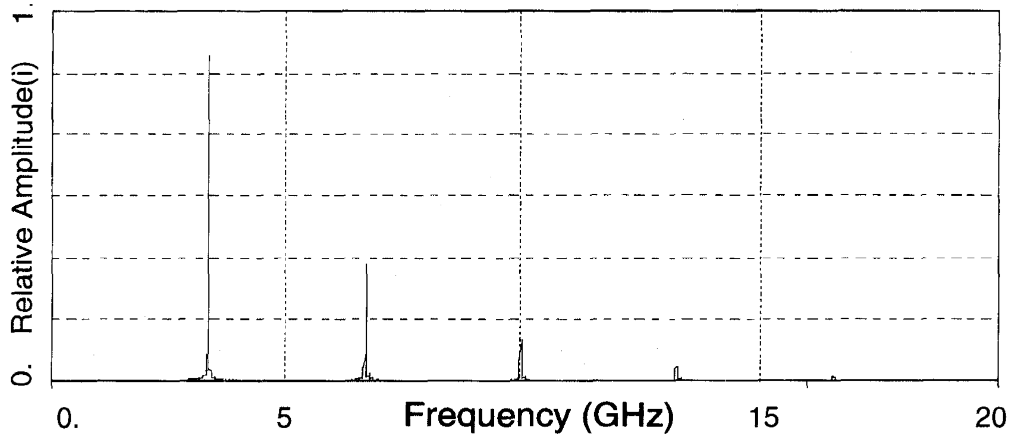

Fig. 7. The Fourier transform of the modulated total current in the 3-D simulation. This plot confirms the absence of nonaxisymmetric modes in the cavity.

radial acceletron allows much lower impedances for the diode, leading to higher input/output powers at lower voltages (~10 kA of current for a 250-kV pulse). In addition, because there is no external magnetic field, the source is small, light, and portable. Also, because there are no foils necessary, potentially high repetition rates are possible.

Numerical simulations have confirmed the viability of the concepts involved. The bunching and the gated emission features of the device are particularly encouraging. Switching to much higher frequencies with little or no drop in the power output is possible. The efficiency (rms), based on preliminary loading simulation results and bunching levels observed, could exceed 50%. The author believes a 2-GW source in the X-band operating at 250 kV with a repetition rate of 1 kHz is possible.

Future work on the radial acceletron is basically optimization and load configuration. Once the loading is designed, a prototype for experimental testing can be built. Integration of the source into the pulser system and the antenna should not present any major problems. Phillips Laboratory is planning an experimental test of the radial acceletron for early 1996.

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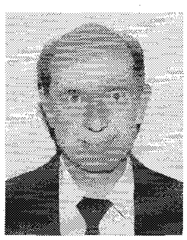

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He joined the Physics Department at Shiraz University in 1972 where he was the Chairman of the Department from 1975 to 1979 and did research in elementary particle physics. He was a Visiting Scholar at UCLA from 1978 to 1979. He joined Mission Research Corporation in 1979 where he worked as a Senior Scientist and Principal Investigator in EMP simulation and HPM source development. He was a National Research Council Associate from 1991 to 1993. He joined the High Power Microwave Source Group at the Phillips Laboratory, NM, in 1993 where he is currently the Chief of the Narrowband Sources Branch in the High Power Sources Division. His current research interests include transit-time oscillators as sources of high power microwave radiation and he has numerically designed five such sources all in the multi-gigawatt range.

Dr. Arman is a member of the American Physical Society.